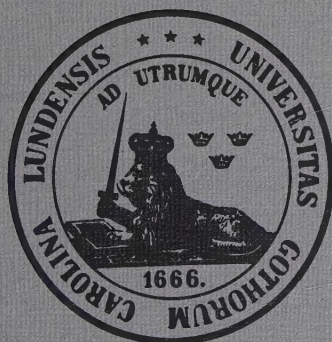


INVESTIGATIONS OF HIGHLY IONIZED ATOMS
USING
FAST IONS AND LASER PRODUCED PLASMAS
WITH
ASTROPHYSICAL APPLICATIONS

BY
CHRISTER JUPÉN



LUND 1985

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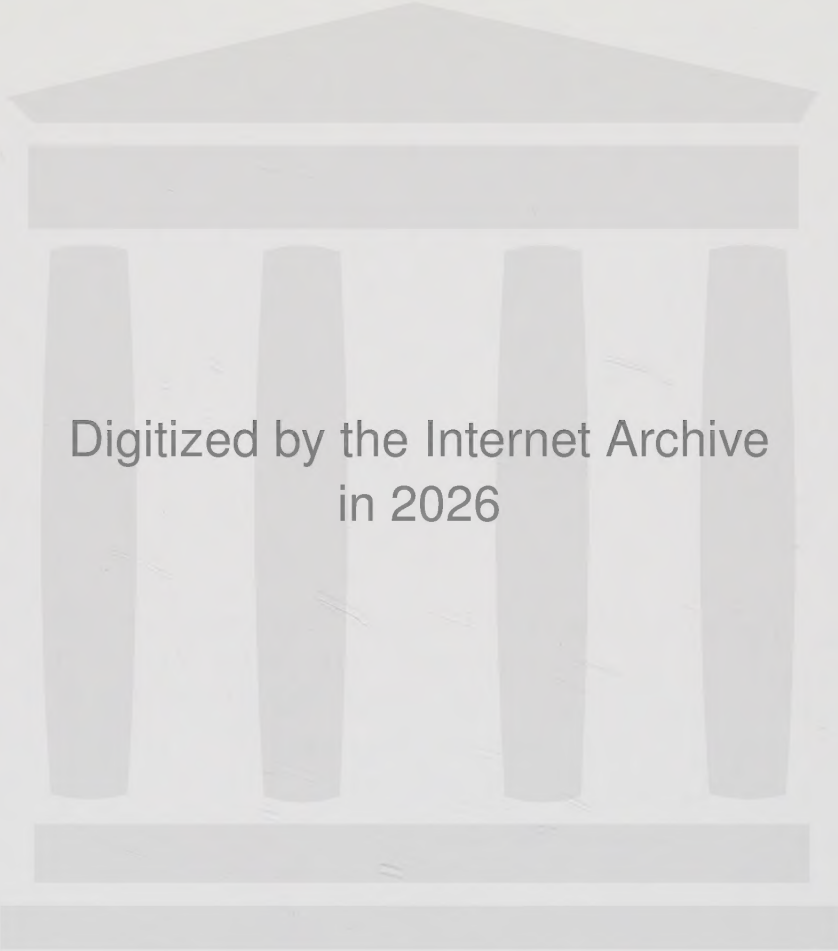
by

Christer Jupén

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AKADEMISK AVHANDLING

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1. Introduction

The present thesis consists of 15 papers which are listed below. Papers 1 - 5 deal with lifetime studies. The other 10 papers are studies of atomic energy levels. A convenient method for such work is to use isoelectronic comparisons [1] to check the analyses and to make predictions for unknown ionization stages in the sequences. This has frequently been done in this thesis.

The following papers will be summarized

1. Lifetimes of the $1s2p^3P_0$ and 3P_2 Levels in F VIII.

L.Engström, C.Jupén, B.Denne, S.Huldt, Weng Tai Meng, P.Kaijser, U.Litzén and I.Martinson.
J.Phys.B 13, L143 (1980).

2. Transition Probabilities for Allowed and Forbidden Transitions from the $1s2p^3P$ Levels in He-like O VII and F VIII.

L.Engström, C.Jupén, B.Denne, S.Huldt, Weng Tai Meng, P. Kaijser, J.O.Ekberg, U.Litzén and I.Martinson.
Physica Scripta 22, 570 (1981).

3. Lifetimes of the $2s2p^1P$ Level in Be-like N IV and O V Obtained from Beam-Foil Experiments and Extensive Cascade Analyses.

L.Engström, B.Denne, J.O.Ekberg, K.W.Jones, C.Jupén, U.Litzén, Weng Tai Meng, A.Trigueiros and I.Martinson.
Physica Scripta 24, 551 (1984).

4. Accurate Experimental Lifetimes of Excited Levels in Sodiumlike Sulfur, S VI.

J.O.Ekberg, L.Engström, S.Bashkin, B.Denne, S.Huldt, S.Johansson, C.Jupén, U.Litzén, A.Trigueiros and I. Martinson.

Physica Scripta 27, 425 (1983).

5. Lifetimes of the $3p\ ^2P_{1/2},\ ^2P_{3/2}$ and $3d\ ^2D_{3/2},\ ^2D_{5/2}$ Levels in Cl VII.

C. Jupén, L.Engström, S.Huldt, A.Trigueiros, J.O. Ekberg, U.Litzén and I. Martinson.

Physica Scripta 29, 226 (1984).

6. Transitions in Multiply Excited F VI and F VII.

I.Martinson, B.Denne, J.O.Ekberg, L.Engström, S.Huldt, C.Jupén, U.Litzén, S.Mannervik and A.Trigueiros.

Physica Scripta 27, 201 (1982).

7. The 3d-4f Transition in S VII Observed in a Laser-Produced Plasma.

C.Jupén, U.Litzén and A.Trigueiros.

Physica Scripta 29, 317 (1984).

8. Identifications of Fe XVII and Ni XIX in Solar Flares Based on Isoelectronic Extrapolations.

C.Jupén

Mon.Not.R.astr.Soc. 208, 1p (1984).

9. The Spectrum and Term System of Cl VII.

C.Jupén, J.Fremberg and B.Fawcett.

Physica Scripta 30, 260 (1984).

10. The $2p^5 3s$, $3p$ and $3d$ Configurations in Neon-Like
Ti XIII and Fe XVII.

C.Jupén and U.Litzén

Physica Scripta 30, 112 (1984).

11. The Spectrum and Term System of Cl VIII.

C.Jupén

Accepted for publication in Physica Scripta.

12. Analysis of the $2p^4 3s$, $3p$ and $3d$ Configurations in
Seven Times Ionized Sulfur, S VIII.

A. Trigueiros and C.Jupén

Accepted for publication in Physica Scripta.

13. The $2p^4 3s$, $3p$ and $3d$ Configurations in Eight Times
Ionized Chlorine, Cl IX.

C.Jupén

Accepted for publication in Physica Scripta.

14. The $2p^4 3s$, $3p$ and $3d$ Configurations in Thirteen
Ionized Titanium, Ti XIV.

C.Jupén, E.Träbert, J.H.Blanke, P.H.Heckman, R.Hucke
and N.Reistad.

Accepted for publication in Physica Scripta.

15. Relativistic Calculation of $2p^5 3s$, $3p$ and $3d$ Energy Levels and Transition Wavelengths in Ti XIII, Fe XVII and Some Other Neon-like Ions.

J.A. Cogordan, S.Lunell, C.Jupén and U.Litzén.

Accepted for publication in Physica Scripta.

2. Lifetime measurements by beam-foil spectroscopy.

After Bashkin [2] and Kay [3] discovered that heavy ion accelerators, previously mainly used for nuclear physics experiments, could be applied in atomic spectroscopy a large amount of atomic data began to appear in the literature. In particular the ease by which lifetimes could be measured was impressive. Thus by analyzing the emitted radiation from the excited ions as a function of the distance from the target foil (usually a thin carbon foil) decay times for levels in many elements and ionization stages were determined. This was of importance in astrophysics, e. g. in the study of element abundances in the sun and stars. In the late 1960's and in the early 1970's several careful theoretical calculations of lifetimes and transition probabilities were also available e.g. [4].

However, a closer inspection showed that in certain cases there appeared systematic discrepancies between the experimental and theoretical lifetimes. Part of this problem could be due to the neglect of some important correlation effects in the theoretical work. On the other hand the discord was persistent also in cases which were comparatively easy to deal with from the theoretical viewpoint, such as the Na-like ions. Even here, certain experimental f -values were about 25% smaller than the theoretically predicted data. Such problems were discussed in the literature, e. g. by Pinnington et al. [5], Wiese and Younger [6] and others. The problem was mainly believed to be due to neglect or incomplete correction of cascading in the analysis of beam-foil data.

Already in 1971 Curtis et al. [7] outlined a technique for extensive cascade corrections, the so-called ANDC-method (Arbitrarily Normalized Decay Curves), but it would take several years before it was routinely used. At our institute we have made ANDC analyses since 1980 using the computer program CANDY [8].

In papers 1 and 2 we made lifetime studies of the $1s2p\ ^3P_J$ levels in He-like O VII and F VIII. For that

purpose we investigated decay curves of the $1s2s\ ^3S_1 - 1s2p\ ^3P_J$ E1 transitions. In a pure coupling this is the only decay channel for the $1s2p\ ^3P$ levels. However, the 3P level can decay through an E1 transition to the $1s^2\ ^1S$ ground state because of mixing with $1s2p\ ^1P_1$. This intercombination line has already for low Z a high transition probability. The 3P_2 level can also combine with $1s^2\ ^1S_0$ through a M2 transition. The probability for this transition also increases rapidly with Z [8]. The $1s^2\ ^1S_0 - 1s2p\ ^3P_0$ transition is strictly forbidden because this is a $J=0$ to $J=0$ transition. However, for atoms with nuclear spin $I \neq 0$ hyperfine-induced E1 transitions from $3P_0$ are possible as is shown in paper 1.

In Fig. 1 the different decay processes from the $1s2p\ ^3P$ levels are indicated. It also shows an isoelectronic comparison of observed lifetimes in the He sequence as well as theoretical calculations by Mohr [9] and Lin et al. [10]. In his paper Mohr [9] investigated the hyperfine structure effects of the $1s2p\ ^3P_{0,1,2}$ levels.

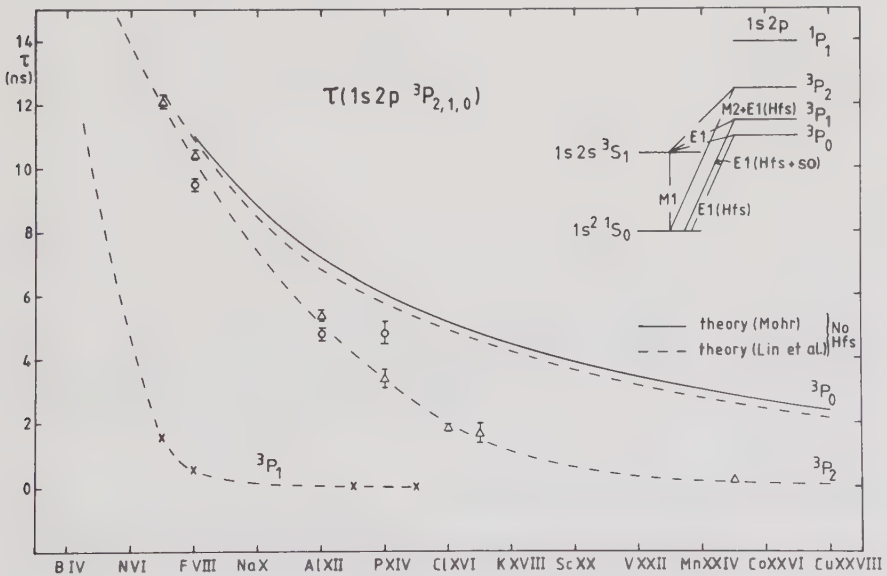


Fig. 1. Isoelectronic comparison of the experimental and theoretical lifetimes of the He-like $1s2p\ ^3P$ levels

His predictions for the hyperfine-quenching of the lifetime have been confirmed for F VIII (Paper 1), Al XIII [11] and P XV [12]. The calculated lifetimes by Lin et al. [10] agree very well with the observations for 3P_1 and 3P_2 in O VII, F VIII (Paper 1), Al XIII [11], P XV [12], Cl XVI [13], Ar XVII [14] and Fe XXV [15] as can be seen in Fig. 1.

In the Be I isoelectronic sequence many early experimental f-values, in particular for the $2s^2\ ^1S - 2s2p\ ^1P$ resonance transition, are significantly lower than the corresponding theoretical results. It was suspected that cascading was the major reason for this discrepancy.

In view of this we performed lifetime measurements in N IV and O V described in paper 3. Here we have studied the cascading into the $2s2p\ ^1P_1$ level in detail and have found that cascading from the $2p^2\ ^1S_0$ level played a particularly important role in the analyses. These were performed using the ANDC technique [8] which takes cascading into account in a very detailed way. The resulting f-values of the $2s^2\ ^1S - 2s2p\ ^1P$ transition in N IV and O V are in good agreement with theoretical calculations.

Papers 4 and 5 deal with lifetime measurements in sodiumlike sulfur (S VI) and chlorine (Cl VII). Lifetimes of the $^2P_{1/2,3/2}$ levels were determined for both ions using beam-foil spectroscopy and the computer program CANDY [8]. In Fig. 2 theoretical and observed f-values are plotted for the $3s\ ^2S - 3p\ ^2P$ transition along the Na-sequence. The continuous curve represents f-values calculated by Lindgård and Nielsen [16] using a numerical Coulomb approximation. The dashed line shows f-values calculated by McEachran and Cohen [17] and Tull et al. [18] who employed the frozen core Hartree-Fock approximation. The f-values of Lindgård et al. [16] are also in very good agreement with those obtained by e.g. Gruzdev et al. [19] and Froese Fischer [4]. The former used a Coulomb approximation based on the semiempirical method of an

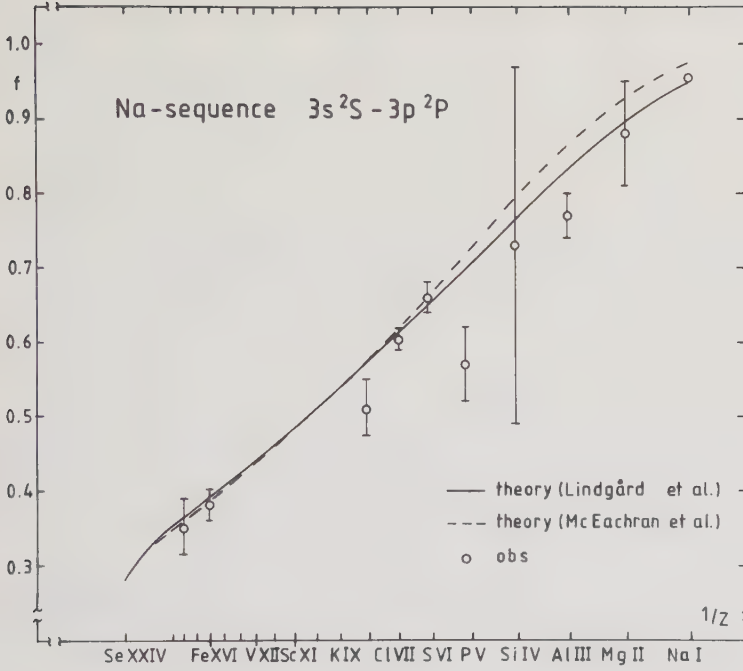


Fig. 2. Isoelectronic comparison of experimental and theoretical f -values for the $3s^2S - 3p^2P$ transition in the Na I sequence.

effective orbital parameter while the latter work employed a frozen core, multiconfiguration Hartree-Fock procedure. From Fig. 2 we can see that our experimental f -values agree with the mentioned theoretical calculations within the experimental error limits.

3. The high power laser system in Lund.

Highly ionized spectra from laser produced plasmas were first reported by Ehler and Weissler [20] in 1966. Subsequently Fawcett et al. [21] observed and identified lines of Fe XV and XVI using a 400 MW ruby laser with 15 nanoseconds pulse duration. A number of spectroscopic results have followed and these show that laser produced plasmas are excellent light sources for the production of highly ionized atoms.

Fig. 3 illustrate the different components involved in the high power laser system at our institute [22,23]. The oscillator cavity contains a neodymium-doped YAG laser rod (1) and a Q-switching device (3) which produces a 3.2 ns pulse. The laser beam is then amplified in a double pass Nd-YAG amplifier (8) and a Nd-glass amplifier (15) to the maximum attainable energy 4.5 J with an rate of 1 pulse per minute. The laser is protected from backscattered radiation by a Faraday rotator. The beam is directed by two dielectric mirrors (16) into the target chamber, where

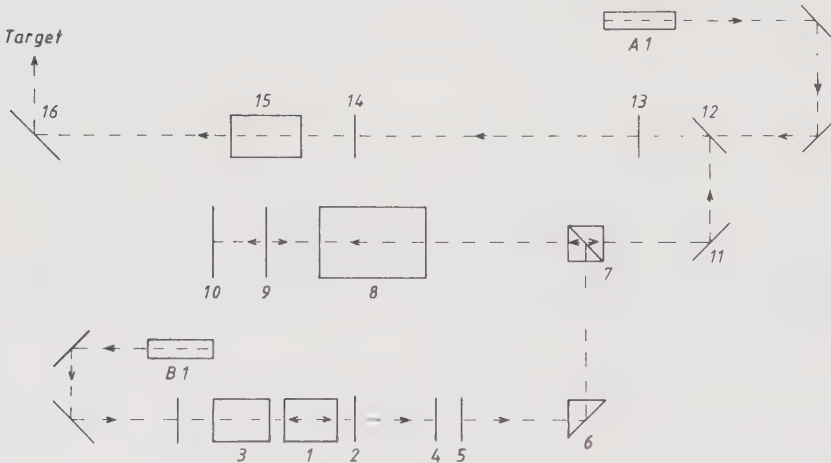


Fig. 3. The high power laser system. The components are:
 (1,8) Nd-YAG amplifiers, (2,10,11,12,16) mirrors
 (3) Q-switch, (4) diaphragm, (5) bleachable cell
 (6) prism, (7) Glan-Thomson prism, (9) $\lambda/4$ plate,
 (13,14) lenses and (15) Nd-glass amplifier.

it is focussed by a lens with 30 cm focal length on a plane target. Lens and target are movable in order to obtain the optimum power density and position of the plasma in front of the spectrograph slit.

The spectra in papers 7 (S) and 10 (Ti-Cr) were recorded with a 3m normal incidence spectrograph (270 - 2500 Å). The laser beam was perpendicular to the target and to the entrance axis of the spectrograph. The spectrograph slit was parallel to the target surface. The plasma was viewed at a distance of approximately 1 mm from the target surface (Fig. 4). The higher ionization stage the smaller conical shape of the distributed ions. With the target in the Sirk's focus this produces a separation of ionization degrees (Fig. 4). For lines with about the same intensity those belonging to the highest ionization stages are the shorter. The majority of the Ti XIII lines could be classified by just viewing the line shape.

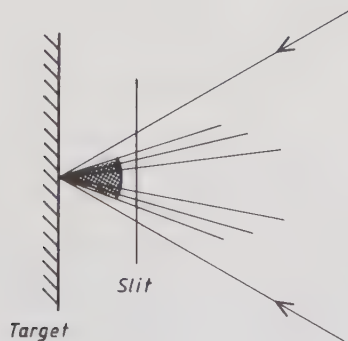


Fig. 4. Ion distribution of the laser plasma (below). The smaller the conical shape the higher charge ions. The different lengths of the spectral lines (above) are related to the ion distribution.

4. Spectroscopic studies.

The spectroscopic studies in this thesis include iso-electronic studies in the Li-, Be-, F-, Ne- and Na-sequences. Spectra from highly ionized F, S, Cl and the iron group elements from K to Ni have been analyzed. Results from a fairly large number of different light sources such as spark, beam-foil and laser produced plasmas have been examined.

In previous sections we have discussed lifetime measurements in highly ionized atoms performed with the beam-foil method. Its favourable properties for obtaining highly ionized atoms together with improved spectral resolution have motivated the present spectral investigations of highly ionized atoms. The study of the $2p^5 3s$, $3p$ and $3d$ configurations in Ne-like chlorine, Cl VIII [24], presented at the beam-foil conference at Quebec 1981, was an initial effort in this field. The laser facility at Lund complements the beam-foil light source in an excellent way. For the experimental equipment used in beam-foil experiments at the 3 MV Pelletron tandem accelerator at Lund we refer to the theses of Huldt [25], Denne [26], Engström [27] and Trigueiros [28] where it is discussed in detail.

4.1 Doubly excited configurations in the Li- and Be-sequence.

The experimental data about the doubly excited $1s2s2p\ ^4P_J$ and $1s2p^2\ ^4P_J$ states have been subject of a number of theoretical studies using a variety of methods. As a starting point for comparison between theoretical calculations and observations I would like to refer to the paper by Chung [29] which was published after our experimental study. Chung also makes a critical comparison between theory and observations. In paper 6 we compared with theoretical works by Hata and Grant [30], Chen et al. [31] and Cheng et al. [32] among others which together with that of

Chung [29] are the latest and therefore expected to take into account all the relevant additional contributions that may have been left out in the earlier calculations. Comparisons between theory and experiment for the $1s2s2p$ and $1s2p^2$ configurations have shown that not only the spin-orbit interaction but also other correlation effects must be taken into account in order to reproduce the $1s2s2p\ ^4P_J$ and $1s2p^2\ ^4P_J$ state theoretically. The methods of the theoretical calculations cited above are shortly summarized:

- a) Hata and Grant [30]: Calculations performed in MCDF + AEL + radiative corrections from QED.
- b) Cheng et al. [32]: MCDF + OL + Breit interaction.
- c) Chen et al. [31]: MCDF + OL + full Breit interaction (also for fine structure calculation).
- d) Chung [29]: Non relativistic part + mass correction term + Darwin term + retardation term (orbit-orbit interaction) + mass polarization + radiative corrections from QED (see Hata and Grant [30]). This package is used for calculation of the term positions.

For calculation of the fine structure which is performed in LSJ scheme the Hamiltonian consists of spin-orbit, spin-other-orbit and spin-spin operators in the Breit-Pauli approximation. As for term position determination QED effects are taken into account (for $Z \geq 6$).

MCDF stands for relativistic multiconfiguration Dirac Fock. AEL means that the program is used in an extended average level mode and OL for an optimization level mode.

For an isoelectronic comparison of the relative center of gravity (c.g.) positions of the $1s2s2p\ ^4P$ and $1s2p^2\ ^4P$ terms the wavenumber divided by the core charge for the c.g. transition between the quartets is plotted in

Fig. 5. We can see that the model by Chung reproduces the observed values in a good way. All other theoretical values are too high (too short wavelengths). However, all models (with exception of points for F VII and Ne VIII in Chen's calculations) show rather regular deviations for $Z \leq 10$ but then the values with exception for those by Chung tend to diverge from the observed values. Chung [29] gives in his paper a detailed description of differences between calculated values from his model and observed data.

Chung also correctly points out the abnormal deviation between center of gravity transition wavelength (calculated from observed multiplet lines) and wavelengths of the individual multiplet lines for some ions along the

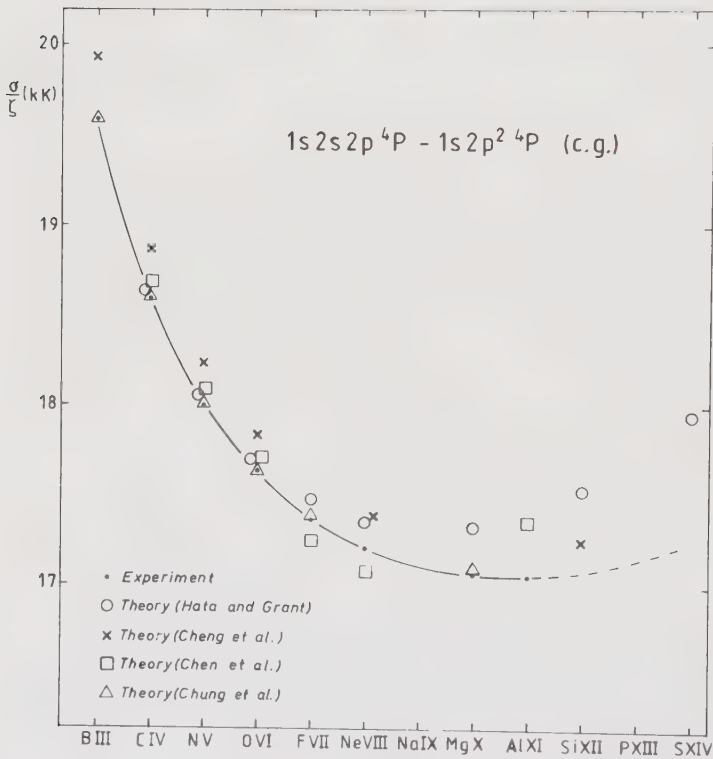


Fig. 5. Isoelectronic comparison $1s2s2p\ ^4P - 1s2p^2\ ^4P$ centre-of-gravity energy difference.

sequence. In Table I corrections are made based on existing observations in those ions. We note that the deviation between theory [29] and observations is consistent in wavelength for O VI - Ne VIII and Mg X (about 0.3 Å) while for C IV and N V the agreement is within the experimental errors. Obviously there is a discontinuity between N V and O VI in the theoretical calculations. As this discontinuity also exist without any QED contributions it seems reasonable to assume that the masspolarization and retardation effects (which are in opposite in sign) not are matched well enough in Chung's calculations.

Table I. Comparison between theoretical calculations by Chung [29] and observations for the center of gravity $1s2s2p\ ^4P - 1s2p^2\ ^4P$ transition (Å).

	<u>B III</u>	<u>C IV</u>	<u>N V</u>	<u>O VI</u>
Ref.29	1701.77	1343.99	1110.4	945.22
Ref.29		1344.22	1110.71	945.61
+ QED				
Obs.	1701.4	1344.2±0.3	1110.65±0.1	946.0±0.1
	<u>F VII</u>	<u>Ne VIII</u>	<u>Mg X</u>	
Ref.29	821.83		585.17	
Ref.29	822.31	726.36	585.93	
+ QED				
Obs.	822.47±0.08	726.62±0.05	586.04±0.5	

In Fig. 6 and 7 the observed fine structure in the $1s2s2p\ ^4P$ and $1s2p^2\ ^4P$ terms are compared with theoretical calculations. We can see that the theoretical fine structures are fairly close to each other while the agreement with observations seems satisfactory. Further observations in more highly ionized atoms may provide more definite information as to the deviation.

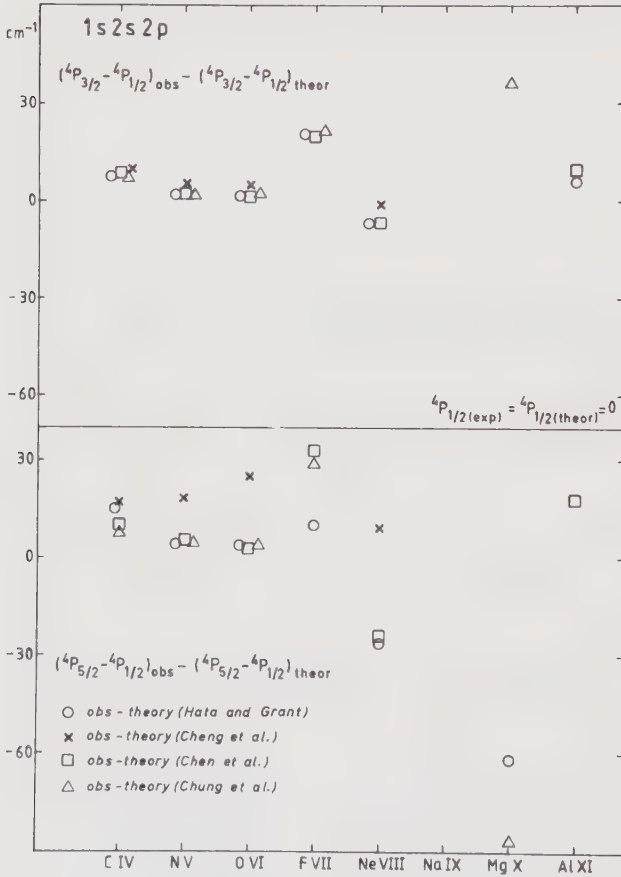


Fig. 6. Isoelectronic comparison of the fine structure of $1s2s2p\ ^4P$ term.

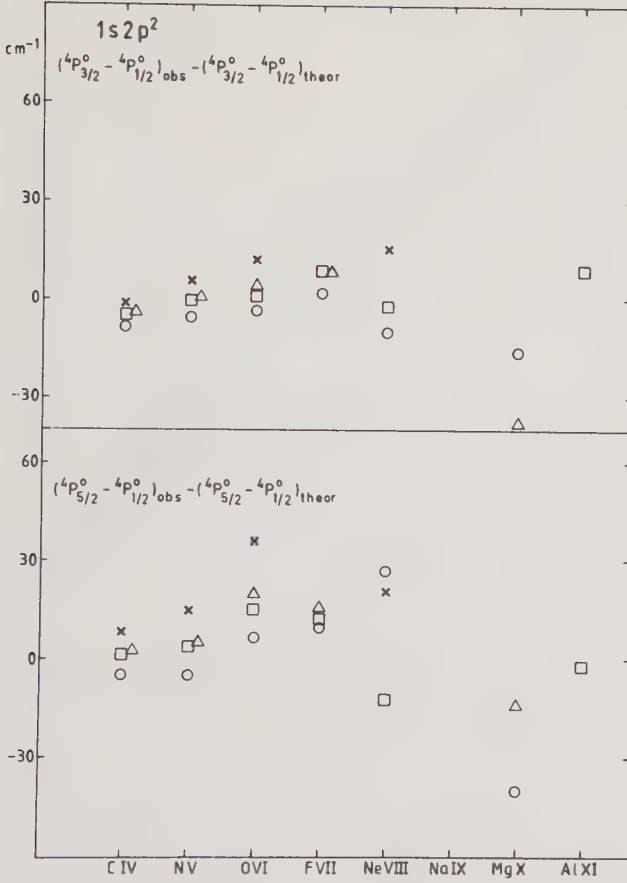


Fig. 7. Isoelectronic comparison of the fine structure of the $1s2p^2$ $4P$ term.

Concerning the fine structure in the $1s2s2p^2$ $5P$ term the agreement with theoretical calculations by Hata and Grant [33] (one of the few available) and observations is perfect (Fig. 8). The relative position of the center of gravity positions of the $1s2s2p^2$ $5P$ and $1s2p^3$ $5S$ terms has been treated in [28].

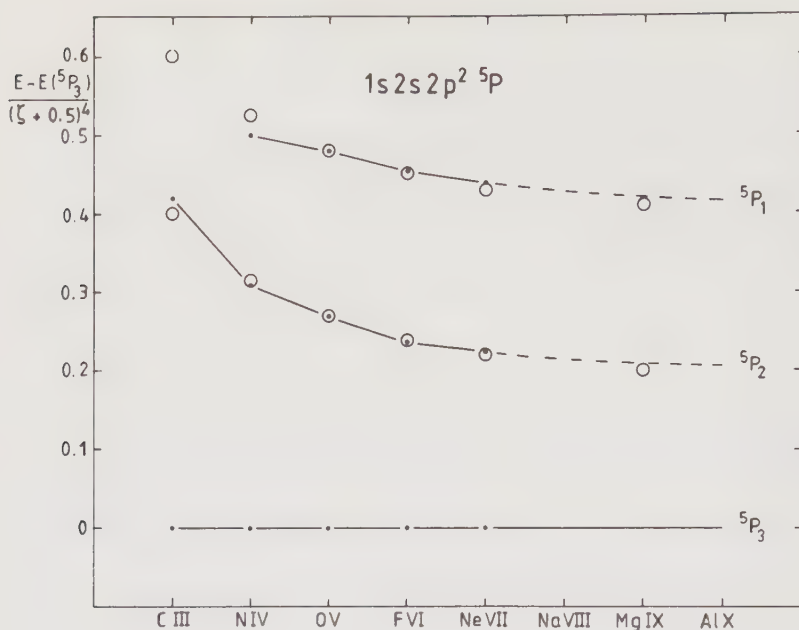


Fig. 8. Isoelectronic comparison of the fine structure of the $1s2s2p^2 \ ^5P$ term in the Be I sequence.

4.2 The spectrum and term system of Cl VII.

The spectrum and term system of sodiumlike Cl VII is given in paper 9. Fig. 9 which originates from the thesis by Joelsson [34] shows that the configurations indicated are practically completely known for ions up to Fe XVI. The Cl VII work may serve as an indicator for the possibilities for combining beam-foil studies with spark measurements to obtain a complete knowledge of a spectrum. Examples of this approach are the analyses of F VI [35] and F VII [36]. In the Cl VII work we had possibilities to check beam-foil wavelengths with those from sliding spark measurements up to 2500 Å. As hydrogenic lines from the spark measurements were very weak and as they also are affected by Stark effect no such line was used as reference line. For this purpose we e.g. used 4s-4p and 4p-4d lines of Cl VI-VII (taken from the spark measurements) as

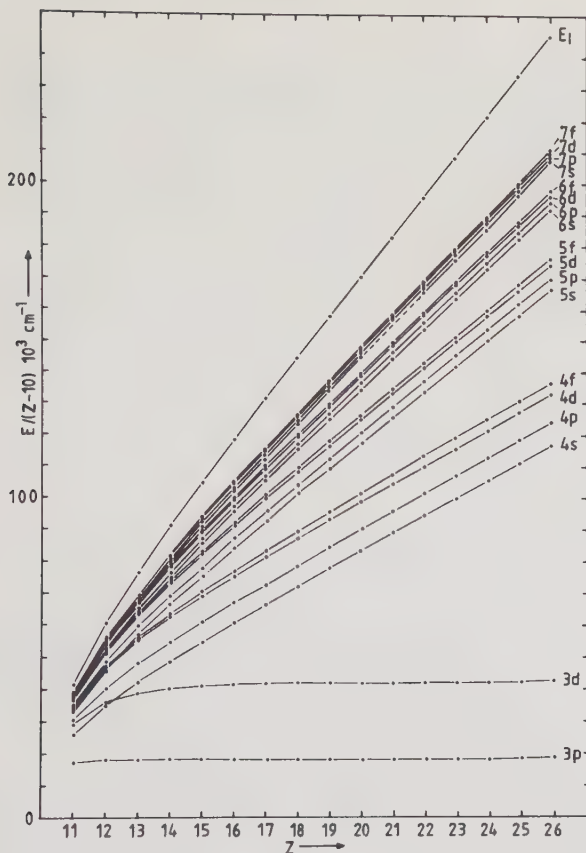


Fig. 9. Isoelectronic comparison of the Na I sequence
(Na I - Fe XVI).

reference lines for the beam-foil wavelength determinations. Different choice and number of reference lines were used. By comparing beam-foil wavelengths not included in the reference list with corresponding spark lines the differences did not exceed $0.05 \text{ \AA}$. Subsequently we believe that the hydrogenic beam-foil wavelengths determined in chlorine to be very accurate.

For predictions of hydrogenic levels ($l \geq 3$) we used values determined by Edlén [37]. Predictions of energy levels with orbitals penetrating the core electrons ($l \leq 2$) Ritz formulae [1] were used. Levels in high excited ns, np and nd configurations were established by means of open spark and laser produced plasma measurements while sliding spark lines were used to establish levels in the lowest

excited configurations.

The ionization energy was determined by means of the polarization formula [1]. Our observations of the ionization energy at $921096 \pm 5 \text{ cm}^{-1}$ and the dipole- and quadrupole polarizability $\alpha_d = (4.37 \pm 0.12)a_0^3 10^{-2}$ and $\alpha_q = (4.75 \pm 0.11)a_0^5 10^{-2}$ are in good agreement with prediction by Edlén [37].

4.3 The neon-like isoelectronic sequence.

The characteristic feature of the structure of neon-like ions is the large energy gap between the ground configuration and the lowest excited configuration. As an example the energy level diagram of neon-like chlorine, Cl VIII, is shown in Fig.10. Ne-like ions have been discussed in several publications during recent years mainly for two reasons, viz. the possibility to use certain transitions for diagnostic purposes in high temperature plasmas [38, 39] and the possibility to achieve inverted population and thus laser action at short wavelengths which will be discussed in section 4.6.2.

Five papers in this thesis deal with ions in the neon-like isoelectronic sequence, viz. 7,8,10,11 and 15. Paper 11 is an extensive analysis of seven times ionized chlorine, Cl VIII, which will be further discussed in section 4.3.1. In paper 10, identifications of 3s-3p and 3p-3d lines in Sc XII, Ti XIII, V XIV and Cr XV from spectra emitted from laser produced plasmas are treated (section 4.3.2). In this paper energy levels of the $2p^5 3s$, 3p and 3d configurations in Ti XIII and Fe XVII are given. The Fe XVII energy levels were derived from lines in solar flare spectra, identified through isoelectronic extrapolation along the neon-like sequence, c.f. paper 8 and section 4.6. A theoretical treatment of the $2p^5 3s$, 3p and 3d configurations, especially in Ti XIII and Fe XVII is discussed in paper 15. Paper 7 contains 3d - 4f lines and the $2p^5 4f$ energy levels in S VII. Perturbations of the 4f

structure were evident in both S VII and Cl VIII and could also be deduced from previous analyses of lower charge states in the sequence. A new project together with Kaufman, Litzén and Sugar [40], concerning the 3d-4f transitions and the perturbation of the 4f structure along the Ne-like sequence from K X to Mn XVI is discussed in section 4.3.4. The cooperation with the Bochum beam-foil group (Träbert et al.) that will be discussed in section 4.4 in connection with the fluorine like sequence has also yielded experimental data on the ng and nh series in Ti XIII in the neon-like sequence.

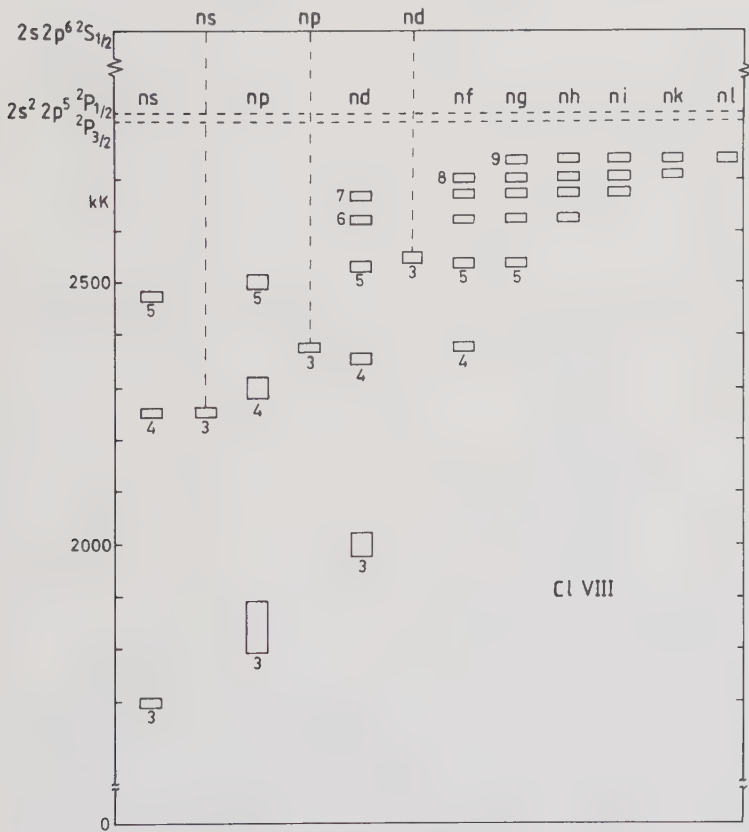


Fig. 10. Energy level diagram of Cl VIII.

4.3.1 The spectrum and term system of seven times ionized chlorine, Cl VIII.

In paper 11 an extensive analysis of the neon-like spectrum Cl VIII mainly based on beam-foil observations is presented. Although the beam-foil method had been used for numerous line identifications and additions to the term systems in various elements and ionization stages, practically no comprehensive term analysis had been previously undertaken with that method. The wavelength region 300-6000 Å was carefully investigated. Examples of beam-foil spectra of chlorine at 7 and 10 MeV are shown in Figs. 11 and 12 respectively, where the most prominent 3p-3d lines in Cl VIII can be seen. Note that the Cl VI (magnesium-like) lines are very weak at 10 MeV, which means that the ionization stages appearing at this energy were mainly limited to sodium-, neon- and fluorine-like ions.

Observations from other light sources were also used in this project. Beam-foil lines were used to connect the upper levels ($n \geq 4$) and levels of the lowest excited $2s^2 2p^5 3l$ configurations. Lines from open spark and laser produced plasma light sources were used to connect levels in the $2p^5 3s$, $3p$ and $3d$ configurations with levels in the $2p^5 4l, 5l$ and $2s 2p^6 3l$ configurations. Totally 200 levels were determined by means of nearly 400 combinations. Fig. 10 shows an energy diagram of Cl VIII where the boxes illustrate the extensions of the configurations. In configurations with $l > 2$ extreme pair coupling was observed. Levels of in the $2s 2p^6 3s$ and $3d$ configurations were found to perturb certain levels in the $2p^5 3p$, $4p$ and nf configurations. E.g. the 3S_1 level in the $2s 2p^6 3s$ configuration is pushing down the 3S_1 level in $3p$ while the 3S_1 level in the $4p$ configuration is displaced upwards. The most drastic configuration interaction occurs between $2s 2p^6 3d$

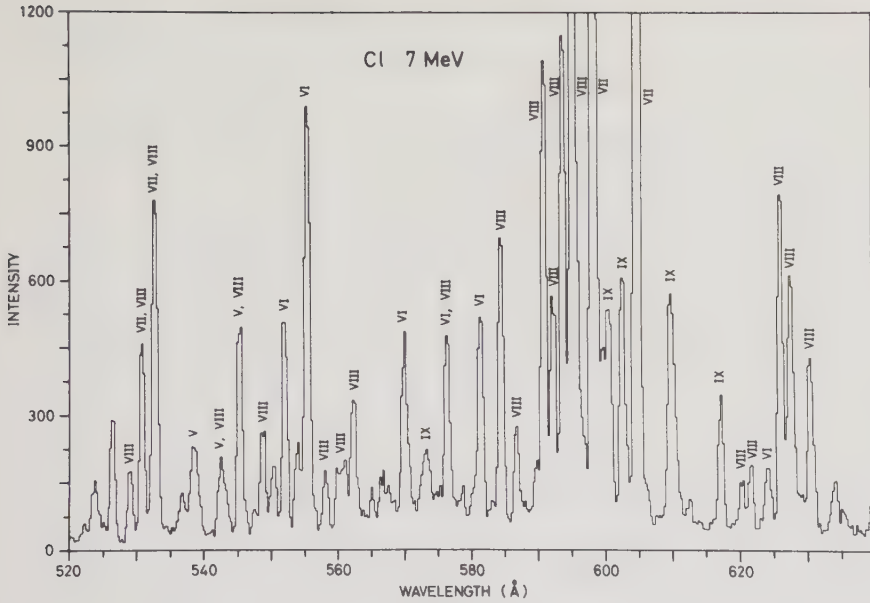


Fig. 11. Beam-foil spectrum of chlorine at 7 MeV.

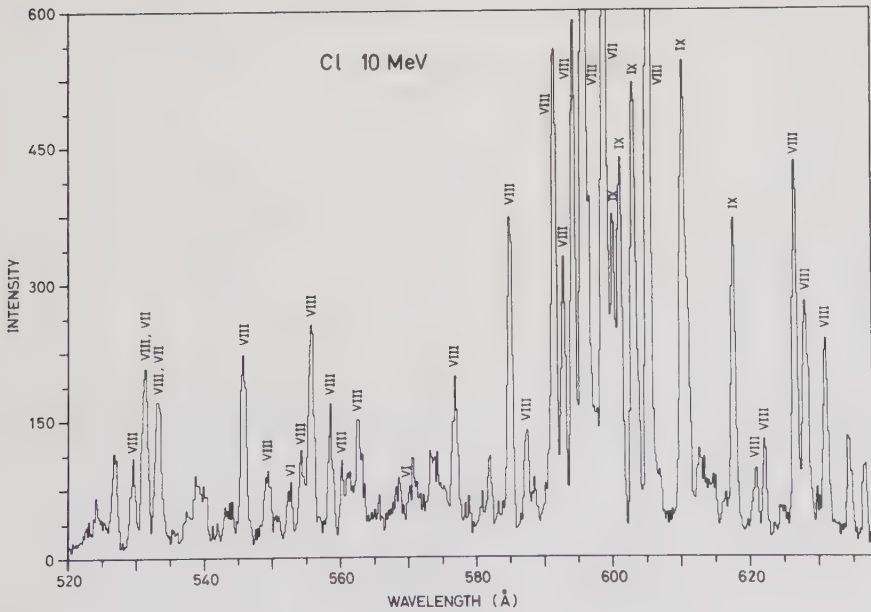


Fig. 12. Beam-foil spectrum of chlorine at 10 MeV.

and $2s^2 2p^5 5f$ where levels with 3D and 1D character are totally mixed. In the $2p^5 4f-8f$ configurations all levels with 3D and 1D character are found to be perturbed. The position of the perturber $2s 2p^6 3d$ can be seen in Fig.10. The perturbation means that these configurations are displaced from the nearly hydrogenic positions, which in turn means that they cannot be used for determination of the ionization energy by means of the polarization formula. A similar but much smaller perturbation on $2p^5 ng$ can be explained as interaction with $2s 2p^6 4f$.

4.3.2 The Ne-like $2p^5 3s$, $3p$ and $3d$ configurations.

When the investigations of Ne-like ions reported in this thesis were started, complete experimental data for the $2p^5 3s$, $3p$ and $3d$ configurations were available only for the six lowest members in the sequence (for references see paper 11). Those experiments had been performed using hollow-cathodes and sliding spark light sources. However, the $J=1$ levels of $3s$ and $3d$ were known up to very high charge states from observations of resonance lines in the soft X-ray region.

Based on isoelectronic extrapolations and comparison of parametric calculations along the sequence around 40 lines were identified as transitions between the $2p^5 3s$, $3p$ and $3d$ configurations in Cl VIII [24]. Later a similar beam-foil investigation in S VII was made, but in this case the result was not published because a paper by Kononov et al. [41] appeared just as our work was ready for submission. A list of our identified $3s-3p$ and $3p-3d$ lines is presented in Table II as a comparison with the work by Kononov et al. The experiment in the latter work was based on observations of a laser produced-plasma and has a wavelength uncertainty comparable to our (0.05 Å).

During the attempts to identify neon-like $3s - 3p$ and $3p - 3d$ lines in solar flare spectra through isoelectronic extrapolation (c.f. section 4.6.1) spectra of highly ionized scandium, titanium, vanadium and chromium from

Table II. Identified (unpublished) 3s-3p and 3p-3d lines
in S VII and comparison with ref. [41].

This work		Ref. [41]		Combination
Int.	$\lambda_{\text{vac}} (\text{\AA})$	Int.	$\lambda_{\text{vac}} (\text{\AA})$	
30	600.95	50	601.16	3p 1P_1 -3d 1P_1
80	608.15	100 bl	608.39	3s 1P_1 -3p 1S_0
150	623.55	170	623.49	3p 3S_1 -3d 3P_2
100 bl	633.33	80	633.35	3p 3S_1 -3d 3P_1
50	638.09	20	638.0	3p 3S_1 -3d 3P_0
30	646.00	20	646.21	3p 3D_3 -3d 1F_3
50 bl	649.18	230 bl	649.0	3p 1D_2 -3d 3D_2
80	662.57	250	662.65	3p 3D_2 -3d 3F_2
bl	671.98	300	671.93	3p 1P_1 -3d 1D_2
300	677.76	400	677.69	3p 3D_2 -3d 3F_2
160	678.94	300 aff	678.80	3p 3D_1 -3d 3F_2
400	680.66	650	680.65	3p 3D_3 -3d 3F_4
280	681.00	620	680.95	3p 3P_2 -3d 3D_3
130	683.60	160	683.59	3p 3P_1 -3d 3D_2
160	686.92	200 aff	686.85	3p 3P_2 -3d 1D_2
300 bl	687.70	350	687.67	3p 1D_2 -3d 1F_3
140	828.43	-	828.43	3s 3P_2 -3p 1D_2
60	844.17	120 aff	844.05	3s 3P_0 -3p 3P_1
100	859.87	60	859.93	3s 3P_1 -3p 1D_2
60	876.96	-	-	3s 3P_0 -3p 1P_1
120	887.82	200	887.74	3s 3P_2 -3p 3D_2
60	893.40	80	893.24	3s 1P_1 -3p 3P_1
80	894.34	70	894.35	3s 3P_1 -3p 3D_1
410	897.82	270	897.82	3s 3P_2 -3p 3D_3
160	903.04	280 aff	903.13	3s 1P_1 -3p 3P_2
320 bl	924.00	340	924.06	3s 3P_1 -3p 3D_2
30	1051.60	80	1051.57	3s 3P_2 -3p 3S_1

laser-produced plasmas were also taken at our institute. Although the neon-like 3s-3p and 3p-3d lines were much weaker than e.g. the corresponding sodium-like lines their shape (length) were conspicuously different from lines of lower ionization stages. Our efforts were mainly concentrated on obtaining the Ti XIII spectrum as complete as possible, and most of the expected 3s-3p and 3p-3d lines were found in this spectrum, whereas so far only the strongest lines have been seen in Sc XII, V XIV and Cr XV. Energy levels based on Ti XIII 3s-3p and 3p-3d lines are given in paper 10.

4.3.3 Relativistic calculation of the 3s, 3p and 3d configurations.

Paper 10 contains comparisons between *ab initio* and parametric calculations of the 3s, 3p and 3d configurations along the neon-like sequence. It was found that the ratios between the fitted energy parameters and the *ab initio* Hartree-Fock integrals asymptotically approached constant values close to unity, which made it possible to extrapolate the term structure with good accuracy. The ratios involving the configuration average energies were, however, found to increase for $Z > 20$, and it was suspected that this behaviour might be caused by the omission of relativistic effects in the Hartree-Fock calculations.

In paper 15 we report about the results obtained from relativistic multi-configuration Dirac-Fock (MCDHF) calculations using the code of Grant et al. [30]. In the paper we compare the calculations with the observations in paper 8 and 10. The conclusion is that the shape of the curves showing the average energy ratio depends on a combination of electron correlations (decreasing with higher Z) and relativistic effects (increasing with higher Z).

The calculations were performed in both single configuration and multiconfiguration mode. In the multiconfigu-

ration case the $2s2p^63l$ configurations were included, and significant interaction between the $2s^22p^53p^3S_1$ and $2s2p^63s^3S_1$ levels was found. In earlier analyses the effective electrostatic integral F^1 had been introduced in order to take care of the deviation of the perturbed $3p^3S_1$ level. Also the $2p^53p^1S_0$ level, which has been discussed by Hansen [42,43], is treated in paper 15. A separate optimization of this state leads to predicted wavelengths for the two $3s - 3p$ lines in Fe XVII involving $3p^1S_0$ that agree perfectly with the observations.

4.3.4 Observations of the $2p^5nf$ configurations along the Ne-like isoelectronic sequence.

Fig.14 shows the relative position of levels in the $2p^54f$ configuration from Al IV [44] to Ar IX [45]. The dashed lines are theoretical values (Hartree-Fock). The observations (points) show that already in Al IV and Si V [46] a slight depression due to the perturbation from the $2s2p^63d$ (abbreviated notation $3d^*$) configuration occurs for certain levels. In S VII, paper 7, we found that the $G^2(2p,4f)$ and $G^4(2p,4f)$ parameters were poorly fitted to the observed energy levels. The same was found for lower ions in the neon-sequence and in e.g. Si V [46] the ratio fit/HF for the $G^2(2p,4f)$ and $G^4(2p,4f)$ parameters was 0.69 and 2.47 respectively. In the final $4f$ fit in S VII in paper 7 the G parameters were fixed at their Hartree-Fock values.

By including the the $3d^*-4f$ interaction integrals scaled to 80% of their HF-values and keeping other parameters than E_{av} fixed at their HF-values a better description of the $4f$ configuration is obtained as shown for Al IV, Si V, S VII and Cl VIII in Table III. It should be noticed that ionization energies determined by means of the polarization formula including the perturbed $4f$ configurations should be revised. In order to further investigate hydrogenic configurations along the neon-sequence and

Table III. Comparison of observed and calculated (Hartree-Fock) energy level values (cm^{-1}) in some Ne-like 4f configurations. The 3d*-4f interaction parameter is kept at 80% of its Hartree-Fock value. Differences between observed and calculated values are given in parenthesis.

	Al IV	Si V	S VII	Cl VIII
(3/2)4f				
$[9/2]_5$	857643(0)	1172886(0)	1928503(0)	2368359(0)
$[9/2]_4$	857646(-4)	1172895(-10)	1928572(23)	2368398(-21)
$[7/2]_4$	858056(13)	1173530(21)	1929745(72)	2369882(42)
$[7/2]_3$	858051(14)	1173499(21)	1929698(58)	2369882(93)
$[5/2]_3$	857810(25)	1173122(38)	1928804(35)	2368574(-13)
$[5/2]_2$	857835(23)	1173182(30)	1929017(18)	2368894(-45)
$[3/2]_2$	857437(26)	1172545(35)	1927682(5)	2367042(-114)
$[3/2]_1$	857410(34)	1172483(42)	1927537(67)	2366767(-69)
(1/2)4f				
$[7/2]_4$	861252(40)	1178241(59)	1939112(149)	2382627(172)
$[7/2]_3$	861247(48)	1178227(81)	1939064(153)	2382560(185)
$[5/2]_3$	861258(54)	1178233(66)	1938964(178)	2382240(240)
$[5/2]_2$	861275(58)	1178272(81)	1939101(177)	2382330(315)

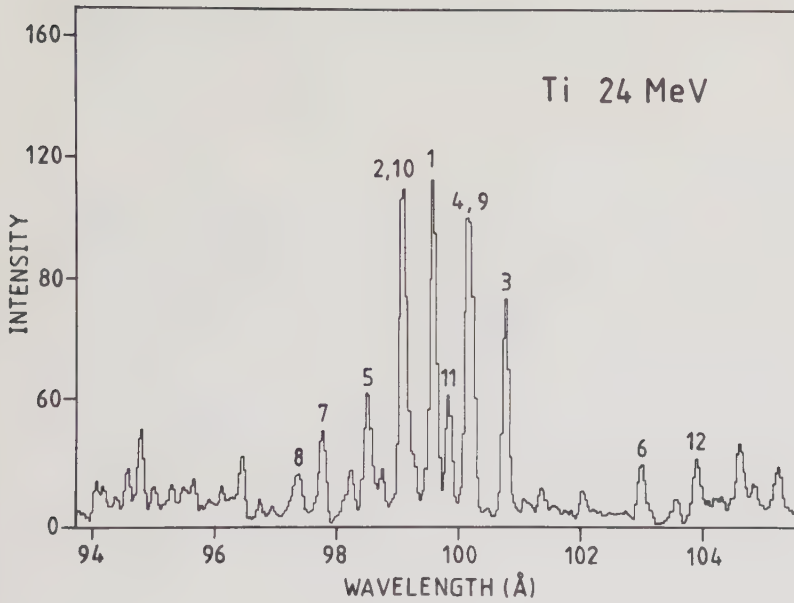


Fig. 13. Beam-foil spectrum of titanium at 24 MeV recorded by Träbert et al. at Bochum.

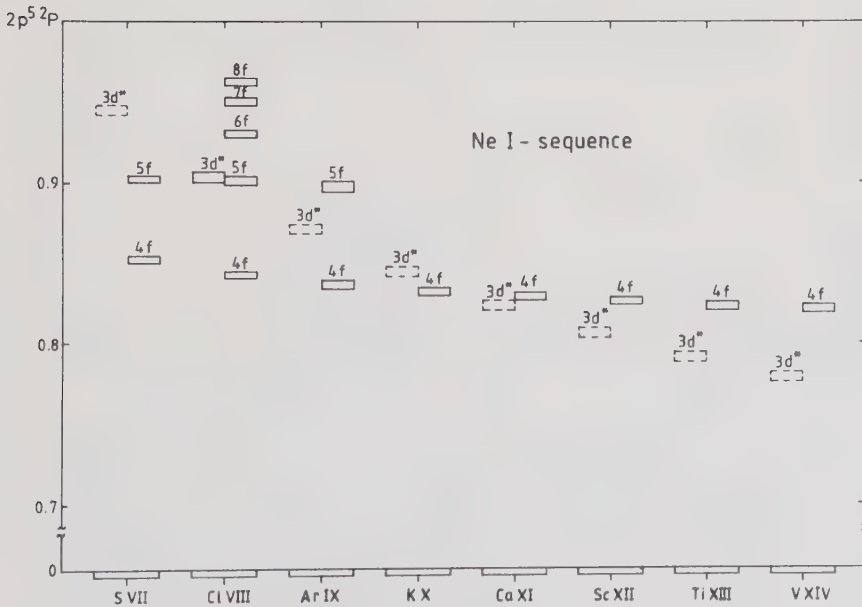


Fig. 14. Relative positions of the $2s^2 2p^6 3d$ and $2s^2 2p^5 4f$ configurations in the neon-sequence.

thereby establish a reliable ionization energies a project in cooperation with the Bochum beam-foil group (Träbert et al.) has been started in Ti XIII [47]. A first order spectrum of titanium at 24 MeV taken at Bochum is shown in Fig.13. The section shows the 3d-4f transition in Ti XIII. The FWHM is only 0.1 Å.

Based on the position of the 3d* configuration in Cl VIII and observed perturbations of the 4f configuration the relative position of 3d* when passing through 4f from S VII to V XIV is schematically shown in Fig. 14. The ionization energy of the 2P limit is taken as the unit for each of the neon-like ions. The 3d* configuration is expected to join the $(2s+2p)^7 31$ complex around $Z=45$, see

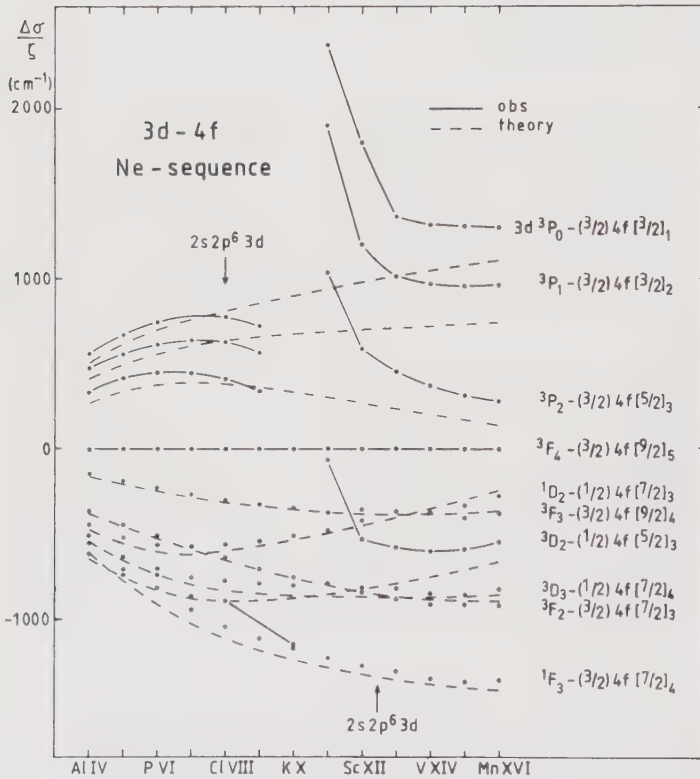


Fig. 15. Isoelectronic comparison of experimental and theoretical of some 3d - 4f transitions in the Ne I isoelectronic sequence.

Edlen[48]. The 4f configuration in S VII is known from paper 7 and 5f from unpublished work. The Cl VIII observations are from paper 11 and Ar IX from Fawcett [49].

From spectrograms recorded at the 10.7m grazing incidence spectrograph at National Bureau of Standards (NBS) an investigation of the 3d-4f transition along the neon-sequence from K X to Mn X VI has been undertaken. The work is in cooperation with Litzén, Kaufman (NBS) and Sugar (NBS). Fig.15 shows the isoelectronic behavior of the 3d-4f transition. The dashed lines are theoretical values and points show the observations. As mentioned earlier only levels with 3D and 1D character are affected by the 3d*-4f interaction. It can be seen from the displacements that the two configurations cross between K X and Ca XI.

4.4 The $2p^4 3s$, 3p and 3d configurations in fluorine-like ions.

The F-like $2p^4 3s$, 3p and 3d configurations are treated in papers 12, 13 and 14, where the beam-foil method has been used. The sulfur (S VIII) and chlorine (Cl IX) data were recorded at the Pelletron tandem accelerator at Lund and titanium (Ti XIV) at the Dynamitron tandem accelerator at Bochum. For the lowest isoelectronic ions up to Si VI [50] triggered and sliding sparks had been used as light sources, but here, as in the neon-sequence, spectroscopy with fast ions is found to be valuable for extending the analysis to higher ions in the sequence.

The energy level structure in the $2p^4 3s$, 3p and 3d configurations is summarized in a number of figures in paper 14. An example of this is shown in Fig.16 where the relative positions of the $2p^4(^3P)3d$ levels are displayed. In Fig. 17 the $E_{av}(fit)/E_{av}(HF)$ for the $2p^4 3l$ configurations are plotted, and the curves show the same general shape as the corresponding curves for the neon-like $2p^5 3l$ configurations in Fig.8 of paper 10. No relativistic calculations have been performed in this case, but the

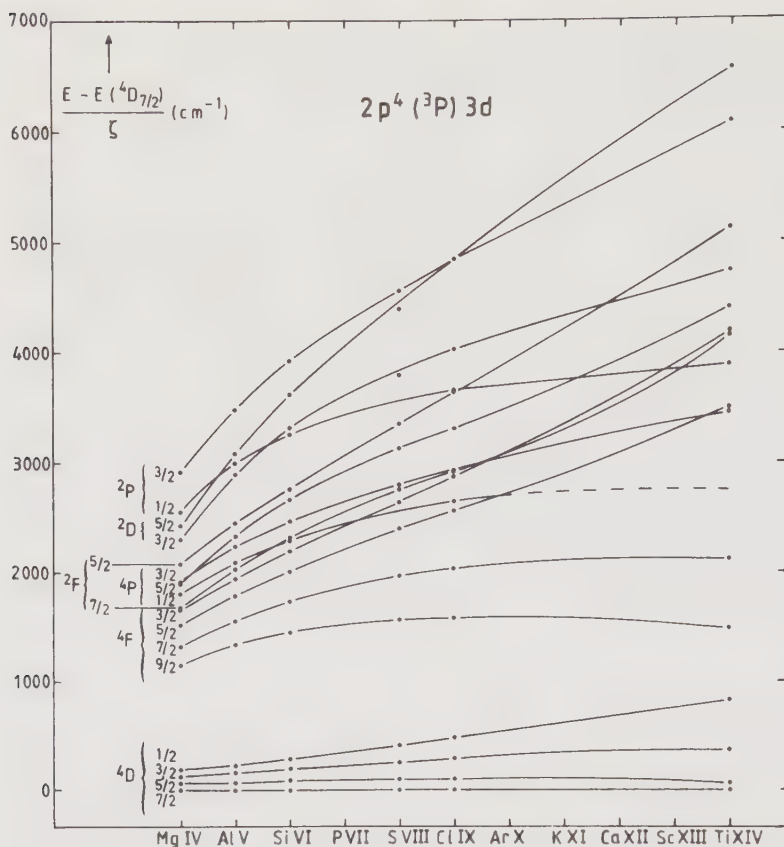


Fig. 16. Isoelectronic comparison of the $2p^4(3P)3d$ levels.

same explanation concerning the trend of the $E_{av}(\text{fit})/E_{av}(\text{HF})$ ratio is most probably valid as for the neon-like sequence, i.e. omission of the relativistic effect in the Hartree-Fock calculation. Fig.18 shows the regular behavior of Slater parameters obtained from the parametric fit to observed levels of the $2p^4 3p$ configuration.

Previously Feldman et al. [51] used a high voltage, low-inductance vacuum spark as a light-source for studying transitions of the type $2s^2 2p^5 - 2s^2 2p^4 3s$ $2s^2 2p^5 - 2s^2 2p^4 3d$ and $2s 2p^6 - 2s^2 p^5 3s$ in K XI to Co XIX. From the measured resonance lines practically all levels in the $2p^4 3s$ and $2p^4 3d$ configurations that can combine with the ground levels were established. Similar investigations using

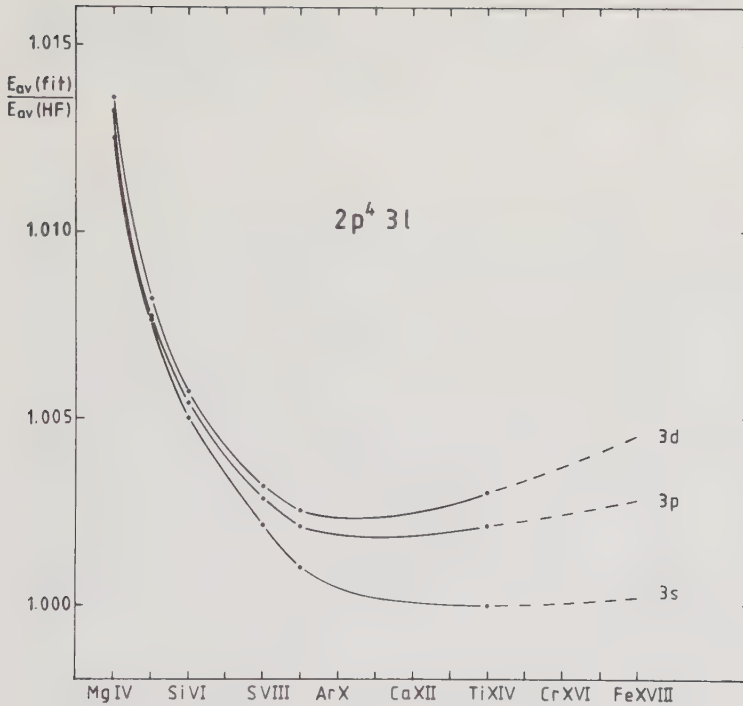


Fig. 17. Ratio between $E_{av}(\text{fit})$ and $E_{av}(\text{HF})$ for the $2p^4 3l$ configurations in the F I sequence.

laser produced plasmas have been made by Boiko et al. [52] (Ni XX and Cu XXI) and [53] (Fe XVIII to Zn XXII, Ge XXIV and Se XXVI). In Ti XIV (paper 14) all such levels are from the work by Feldman et al. [51]. The branching ratios from these resonance levels do not permit any beam-foil observation of the weak channels from 3d levels with $J=5/2$ to 3p levels. A possibility to get all the 3d levels established with the beam-foil technique would be by the identification of 3d-4f transitions.

Based on the analyses of S VIII, Cl IX and Ti XIV interpolated wavelengths for some transitions between levels in the $2p^4 3s$, 3p and 3d configurations are given in Table IV.

Table IV. Predicted 3s-3p and 3p-3d lines in P VII, Ar X, K XI, Ca XII and Sc XIII (in Å). The uncertainty is estimated to be less than ± 0.7 Å.

		P VII	Ar X	K XI	Ca XII	Sc XIII
$(^3P)3s - (^3P)3p$						
4P	$5/2 - ^4P 5/2$	1096.8	763.7	691.3	630.3	578.4
	$5/2 - 3/2$	1081.4	751.9	681.4	622.5	572.8
	$3/2 - 1/2$	1110.4	777.0	703.3	641.0	587.2
4P	$5/2 - ^4D 7/2$	971.0	677.2	613.0	558.7	512.1
	$3/2 - 5/2$	990.7	705.3	644.7	593.5	549.8
	$3/2 - 3/2$	967.9	673.8	608.7	553.0	504.0
	$1/2 - 1/2$	983.3	694.7	632.4	580.7	536.0
2P	$3/2 - ^2D 5/2$	1044.9	724.1	652.6	592.3	540.7
$(^1D)3s - (^1D)3p$						
2D	$5/2 - ^2F 7/2$	1035.9	720.4	652.1	594.2	544.6
	$3/2 - 5/2$	1048.1	738.5	672.1	616.6	569.4
2D	$5/2 - ^2D 5/2$	921.6	642.3	581.9	531.0	487.6
	$3/2 - 3/2$	927.6	651.8	592.6	543.2	501.1
$(^1D)3p - (^1D)3d$						
2F	$7/2 - ^2G 9/2$	790.6	556.9	507.4	466.3	431.3
	$5/2 - 7/2$	785.0	547.9	497.5	455.4	419.5
2D	$5/2 - ^2F 7/2$	788.6	549.2	499.0	457.4	422.3
$(^3P)3p - (^3P)3d$						
4D	$7/2 - ^4F 9/2$	772.2	543.8	495.8	455.8	421.7
	$5/2 - 7/2$	772.2	541.6	491.4	450.2	415.5
4P	$5/2 - ^4D 7/2$	764.9	541.7	493.7	453.4	418.7
2D	$5/2 - ^2F 7/2$	787.5	549.1	500.0	459.2	424.6

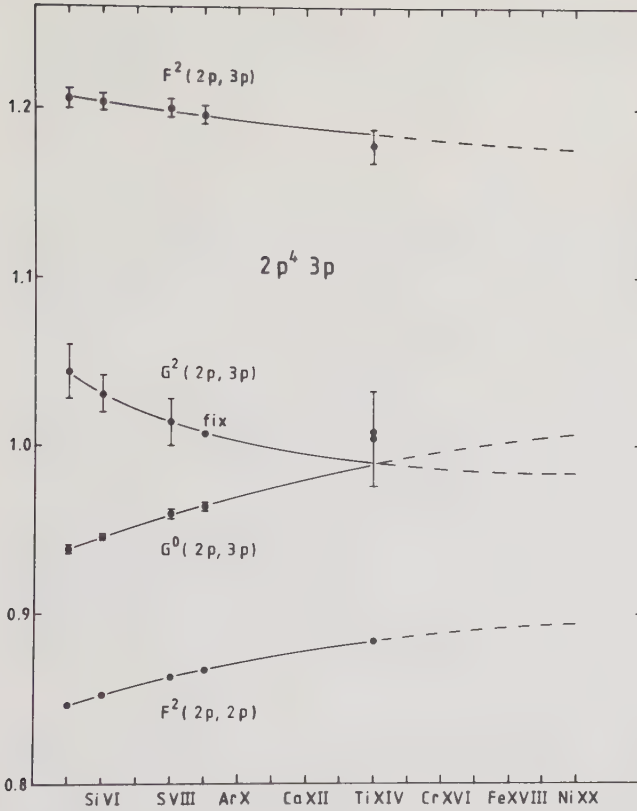


Fig. 18. Isoelectronic comparison of the fitted Slater parameters of the $2p^4 3p$ configuration in the fluorine sequence.

4.5 Level designations for the Ne-like and F-like ions.

The coupling conditions along an isoelectronic sequence generally change with increasing Z . While the LS representation may be a good approximation in the beginning of the sequence, the conditions at high Z approach the jj approximation. Thus the levels for low Z can be unambiguously given LS names, as is e.g. the case for the $2p^5 3s$ configuration in Ne-sequence, where the three low levels form a 3P while the upper level is a 1P . An

investigation of LS eigenvector components shows, however, that the $J=1$ levels get increasingly mixed in the LS scheme as Z increases, and in fact the largest component of the upper level changes from 1P to 3P . This situation gives rise to confusion regarding the level designations, as some authors use the maximum LS eigenvector component as level designation instead of keeping the ordering of the $J=1$ levels from the region of the sequence where the LS scheme is a meaningful approximation. Thus the upper $J=1$ level should be called 1P until the designation is changed to the jj scheme. In fact there is good reason to make this change early in the sequence - already for Sc XII the average purity of the $3s$ configuration is 94% in jj -coupling and only 58% in LS-coupling. The isoelectronic development of the Ne-like $3s$ level structure is shown in Fig.2 in paper 10. The F-like $3s$ level structure changes more slowly from LS- to jj -coupling. Here the average purity of the $3s$ configuration in Ti XIV is 86% in LS- and 81% in jj -coupling.

For the Ne-like $2p^5 3p$ configuration the average purity in Si V is 76% in LS- and 66% in jj -coupling. Corresponding percentage values for Cl VIII and Ti XIII are 73% in LS-, 70% in jj - and 70% in LS- and 77% in jj -coupling respectively. Looking at the structure for each J -value we find that already for Si V the $J=2$ levels have higher purity in jj -coupling (85% jj and 69% LS). Consequently there is no reason to change the LS designation along a smooth isoelectronic curve because the maximum eigenvector compositions in the LS scheme change. The change should be made to jj designations instead. It is worth noting that the two $J=0$ levels 3P_0 and 1S_0 are mainly responsible for keeping the average LS purity higher than the jj purity in the Ne-like $3p$ configuration. The mixing in the Ne-like $3p$ configuration has been discussed in detail by Bureeva and Safronova [54], who point out that as since for $3s$, the only unambiguous LS designations are those obtained by application of the rule that levels with same J do not cross, i. e. the ordering of the levels for a certain J value should be retained from the beginning of

the sequence as shown in Fig.2 paper 10. The diagram which was obtained through Hartree-Fock calculations, also shows the correlation between the LS and jj designations.

In the 3p configuration of the F-sequence the situation is somewhat different. Here e.g. in Sc XIII the average LS- and jj-purity of the configuration is 70% and 66% respectively. We have to go up to V XV before $J=5/2$ levels are better described in the jj scheme. Considering the $(^3P)^2P_{3/2}$ and $(^3P)^2D_{3/2}$ levels in the F-like 3p configuration we note (paper 14) a gradual change of eigenvector composition in the LS-scheme along the sequence for these levels. Between Si VI and S VIII the maximum eigenvector composition has been reversed. As the LS purity of the $J=3/2$ levels in S VIII is 85% in comparison to 53% jj purity this is really a case where the LS designations should be changed along an isoelectronically smooth curve.

The coupling development for the Ne-like 3d configuration is rather similar to that for the 3p configuration. In Cl VIII the average purity of the 3d configuration is 74% in LS- and 70% in jj-coupling. In Si V where the average purity for the 3d configuration is 77% in LS- and 66% in jj-coupling, the purity of the $J=3$ levels is 69% and 85% respectively. The designations given for $J=3$ levels early in the sequence should be retained, although the maximum eigenvector composition changes, until the jj-scheme is adopted.

Also for the F-like 3d configuration the situation is similar to 3p. Here e.g. $(^3P)^2F_{5/2}$ and $(^3P)^4P_{5/2}$ interact, which has two consequences:

1. The levels repel each other, which is seen as an avoided crossing of the isoelectronic curves (Fig.16).
2. After the avoided crossing the states get high LS purity again, but with an interchange of the maximum eigenvector component.

4.6 Applications.

4.6.1 Astrophysical application in Fe XVII.

" Solar flares are complex transient excitations of the solar atmosphere above magnetically active regions of the surface involving enhanced thermal and radio emission, hard X-rays, cosmic rays and plasma ejection. Their origin is not yet understood after more than a century of study since the first recorded observations " [55].

To judge from the literature on solar flares the statement above, which is quoted from Brown and Smith [56] in a comprehensive review article, seems to hold also 1985. The central problem of solar flares is the complex energy release. However, since 1969 a large amount of observational data has become available with the aid of space-borne instruments in the XUV and at shorter wavelengths. During this time (since 1969) substantial progress has been made in laboratory plasma physics and theoretical studies on this subject. One of the reasons why the statement by Sweet [55] is relevant may be the overwhelming task to effectively compile all information [56].

From the available solar flare lists (200-600 Å) [57-59] 24 lines could be identified as 3s-3p and 3p-3d transitions in Fe XVII (paper 8) by means of our laboratory measurements and theoretical calculations .It should be noticed that these lines have not yet been identified in laboratory recordings. In a quite recent paper Feldman et al.[60] confirmed the majority of the identifications by examining solar flare spectrohelio- grams. It was found that the shape of these lines differed from lines of lower ionization states. Feldman et al. also suggested a few changes of identifications, and the changes are now confirmed by the relativistic calculations in paper 15.

By a further examining of solar flare line lists following identifications by comparing with existing laboratory data in Mg III [61] and Si V [46] can be made (Table V.)[62].

Table V. Solar flare identifications by comparing existing laboratory data in Mg III [61] and Si V [46]. The wavelengths are taken from XUV spectra of the June 15, 1973 solar flare observed from Skylab [62]. The wavelengths are expressed in Å.

Mg III		Si V	
	Lab.	Lab.	Flare
$3s\ 3P_2-3p\ 3D_3$		1251.390	1251.39
$3p\ 3D_3-3d\ 3F_4$	1738.835		17838.81

4.6.2. Prediction of 3s - 3p and 3p - 3d wavelengths in Fe XVIII.

In the recent paper mentioned above [60] Feldman et al. noticed that the intensities of the Na-like Fe XVI 3s-3p and 3p-3d lines are 100 times larger than the corresponding lines in Fe XVII. The corresponding fluorine-like Fe XVIII lines can therefore be expected to be still weaker.

Based on the newly made analyses in S VIII (paper 12), Cl IX (paper 13) and Ti XIV (paper 14) and those for lower ions extrapolations of the wavelengths for the 3s-3p and 3p-3d transitions are made to Fe XVIII, Fig. 19. The wavelengths positions were compared to solar flare lists of Widing [57], Dere [58] and Sandlin [59].

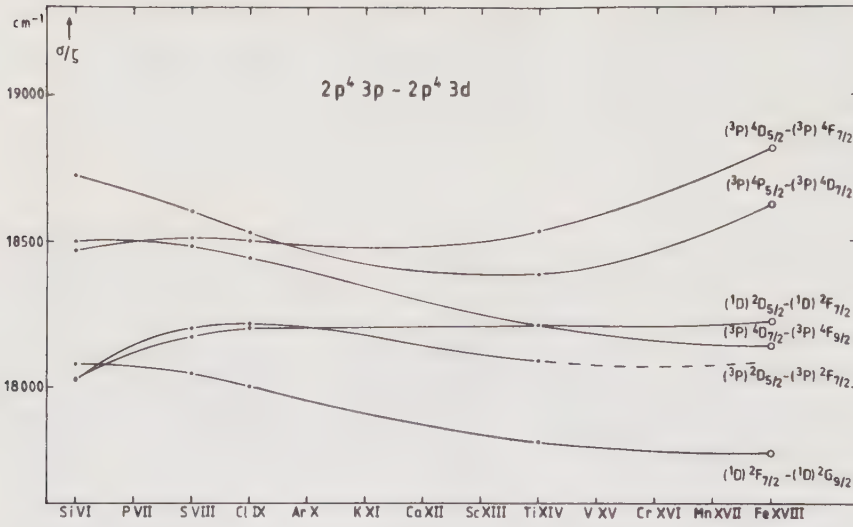


Fig. 19. Isoelectronic comparison of some 3p - 3d transitions in the F I sequence.

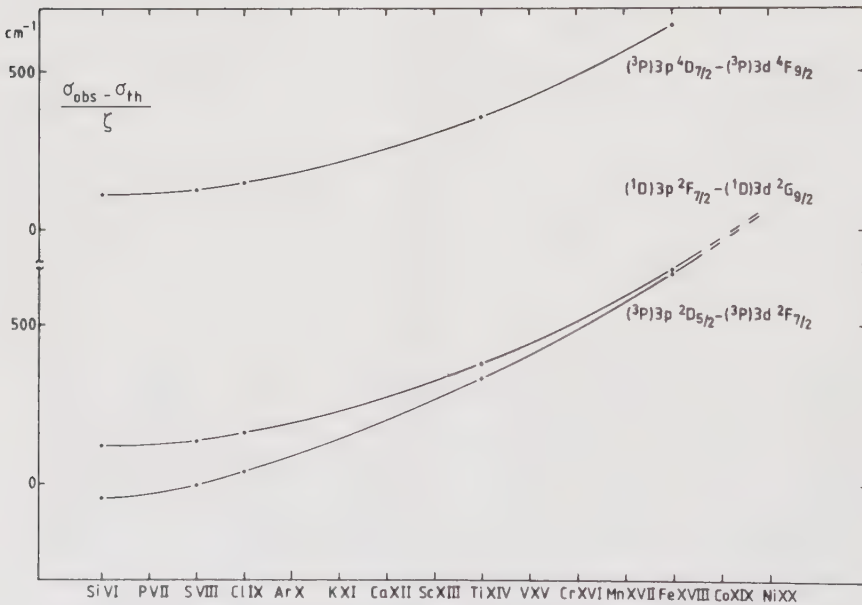


Fig. 20. Isoelectronic comparison the difference between observed and calculated wavenumbers for some 3p - 3d transitions in the F I sequence.

An example of an isoelectronic comparison of the difference between observed and theoretically calculated (HF) wavenumbers divided by the core charge for some 3p-3d lines are shown in Fig.20. Table VI contains tentative identifications and predictions of solar flare lines in Fe XVIII.

Table VI. Solar flare identifications of 3p-3d lines in Fe XVIII.

Int.	$\lambda(\text{\AA})$	Combination	Temp class ^a
a b			
4 -	297.34	$(^1D)3p \rightarrow ^2F_{5/2} - (^1D)3d \rightarrow ^2G_{7/2}$	I-II
4 -	298.22	$(^3P)3p \rightarrow ^4P_{5/2} - (^3P)3d \rightarrow ^4D_{7/2}$	I-II
		$(^3P)3p \rightarrow ^4D_{5/2} - (^3P)3d \rightarrow ^4F_{7/2}$	
-b1 MnXIV	304.80	$(^1D)3p \rightarrow ^2D_{5/2} - (^1D)3d \rightarrow ^2F_{5/2}$	
-	306.29	$(^3P)3p \rightarrow ^4D_{7/2} - (^3P)3d \rightarrow ^4F_{9/2}$	
- FeXI	308.54	$(^3P)3p \rightarrow ^2D_{5/2} - (^3P)3d \rightarrow ^2F_{7/2}$	
b1 FeXV	312.18	$(^1D)3p \rightarrow ^2F_{7/2} - (^1D)3d \rightarrow ^2G_{9/2}$	

^a From the solar flare list of Sandlin [58]

^b From the solar flare list of Dere [59]

4.6.3 Population inversion in neon-like ions.

The $2p^5 3p \rightarrow ^1S_0$ level discussed in section 4.3.3 is interesting as the $3s \rightarrow ^1P - 3p \rightarrow ^1S$ transition is supposed to be one of the main candidates for amplification in Ne-like ions. The attempts during recent years to achieve amplification of radiation at short wavelengths have stimulated much theoretical activity on neon-like atomic system [63-67]. The work that resulted in the successful observations of amplified emission from selenium and yttrium plasmas [68,69] included comprehensive calculations of plasma properties and atomic data. Fig.21

shows the scheme for population inversion in neon-like ions. Levels in the $2p^5 3s$, $3p$ and $3d$ configurations are populated by electron collisional excitation from the ground configuration $2p^6$. Of the $3p$ levels only 1S_0 and 3P_0 are populated by direct excitation from the ground configuration. The other $3p$ levels are populated through cascading from upper levels. Electric dipole (E1) transitions from $3p$ to the ground state are forbidden whereas $3s$ 3P_1 and 1P_1 decay very rapidly to the ground state. As the decay rate from $3p$ to $3s$ is much slower this leads to a population inversion between the $3p$ and $3s$ levels. Relativistic calculations of the kind discussed in section 4.3.3 have been performed [30] for the two ions where amplifications of $3s$ - $3p$ emission has been reported

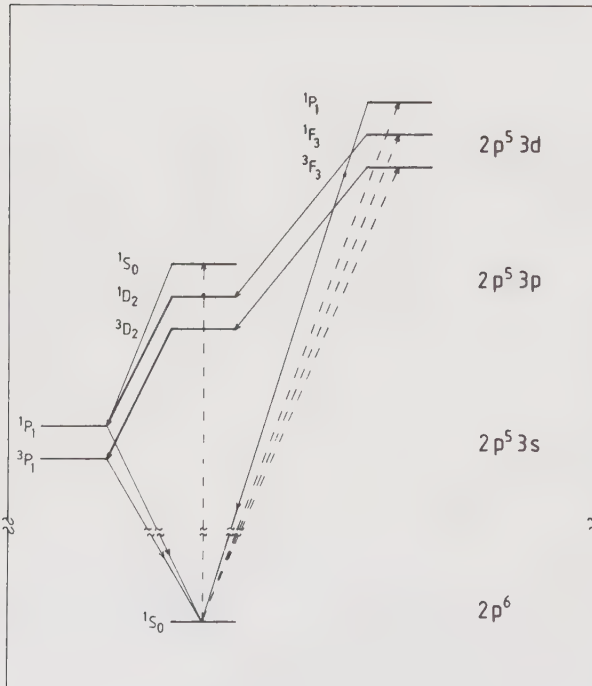


Fig. 21. Lasing scheme for Ne I like ions.

[68,69] namely Se XXV and Y XXX. The resulting wavelengths are shown in Table VII for the two transitions where amplification was observed and the transition that was expected to give the strongest amplification. The agreement with the reported wavelengths is found to be very good.

Table VII. Laser wavelengths of 3s-3p lines in Se XXV and Y XXX.

		Wavelengths (Å).			
<u>Level designation</u>		<u>Se XXV</u>		<u>Y XXX</u>	
3s	- 3p	obs. ^a	calc.	obs. ^a	calc.
$(1/2, 1/2)_1$	- $(1/2, 1/2)_0$	(183) ^b	181.7		154.3
$(1/2, 1/2)_1$	- $(1/2, 3/2)_2$	209.6	209.7	157.1	157.2
$(3/2, 1/2)_1$	- $(3/2, 3/2)_2$	206.3	206.4	155.0	155.0

^a Ref. 69.

^b Prediction in ref. 69.

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